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RESPONSE OF BURIED VERTICALLY ORIENTED CYLINDERS TO DYNAMIC LOA--ETC(U)
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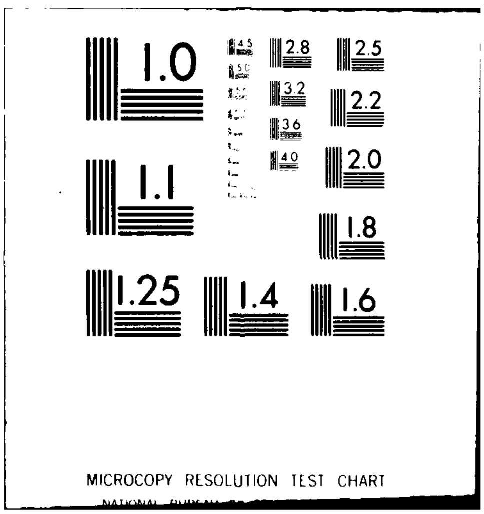
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RESPONSE OF BURIED VERTICALLY ORIENTED CYLINDERS TO DYNAMIC LOADING

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INTRODUCTION

One of the primary concepts proposed for basing advanced ballistic missile systems is to emplace the missile in a buried vertical cylindrical shelter. Since little data were available on the response of vertically oriented cylinders that could be used to assess the hardness of missile silos, a field test program was conducted by the Structures Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) to determine the response to failure of generic vertical shelters having different wall construction designs and subjected to the effects of simulated nuclear surface overpressure loadings. Results obtained from the simulation program were to provide information to support selection and design of prototype vertical shelters.

The specific objective of the field test program was to obtain information whereby cylinder wall construction designs could be ranked as to their survivability/vulnerability. Thus, with such information, the cost performance of the various designs could be determined with structural hardness a major consideration.

This paper summarizes the results of three dynamic tests conducted on vertical cylinders in a dry sand with wall designs consisting of plain concrete with an inner liner, plain concrete with shear studs and an inner liner, and reinforced concrete without an inner liner. Using the experimental results in which three different wall thicknesses were tested for each design and considering relative costs, a candidate wall design for the vertical shelters is presented.

TEST PROCEDURES

To accomplish the objective of the investigation, three field tests utilizing the FOAM High-Explosive Simulation Technique (FOAM HEST) test environment were conducted at the Fort Polk Military Reservation in Louisiana, site of previous field tests conducted by WES. The three tests were identified as Dynamic End on Tests (DEOT) in which three cylinders were included in each test (Figure 1), i.e. the DEOT 1 cylinders were constructed of plain concrete with steel inner liners, the DEOT 2 cylinders were constructed of plain concrete with shear studs and steel inner liners, and the DEOT 3 cylinders were constructed of reinforced concrete without inner liners. The scale-model cylindrical structures had a 0.61-metre (2-foot) inside diameter and an overall length of 1.83 metres (6 feet). The only construction variable for the cylinders in a specific test was the wall thickness which was 4.32, 7.11, and 10.16 cm (1.7, 2,8, and 4.0 inches). The end caps for the cylinders consisted of a steel shell filled with high-strength concrete; however, the end caps were not designed to be test articles. The average concrete compressive strength of the cylinders on test day was 44.0 MPa (6,380 psi).

The three DEOT test beds were excavated to 3.05 metres (10 feet) deep, the structures placed, and then backfilled with clean, dry sand. After a test bed was excavated, circular foundation blocks with hold down rods were placed in the bottom of the bed on preleveled surfaces. The vertical cylinders were then placed on their foundations (Figure 2) and instrumentation connections made. The dry sand was placed in 15.2-cm (6-inch) lifts with each lift receiving three vibration passes (Figure 3) to obtain the desired density of 1681 kg/m^3 (105 pcf).

During the tests, electronic measurements were made to obtain the airblast surface overpressure, vertical soil stress, relative vertical deformation of certain cylinders, and strain in the concrete of the cylinder walls. The strain gages were mounted either vertically or radially at locations of 0.61 metres (2 feet) and 1.22 metres (4 feet) from the top of the cylinders.

The test environment was generated by uniform FOAM HEST's over the test bed areas, as generally shown in Figure 1. An 11.4 cm (4.5 inch) charge cavity was filled with polystyrene and evenly distributed strands of 2.86-cm (1-1/8-inch) diameter Iremite explosive. A sand overburden of 0.81 meters (32 inches) was placed over the explosive to control the duration of the pressure pulse.

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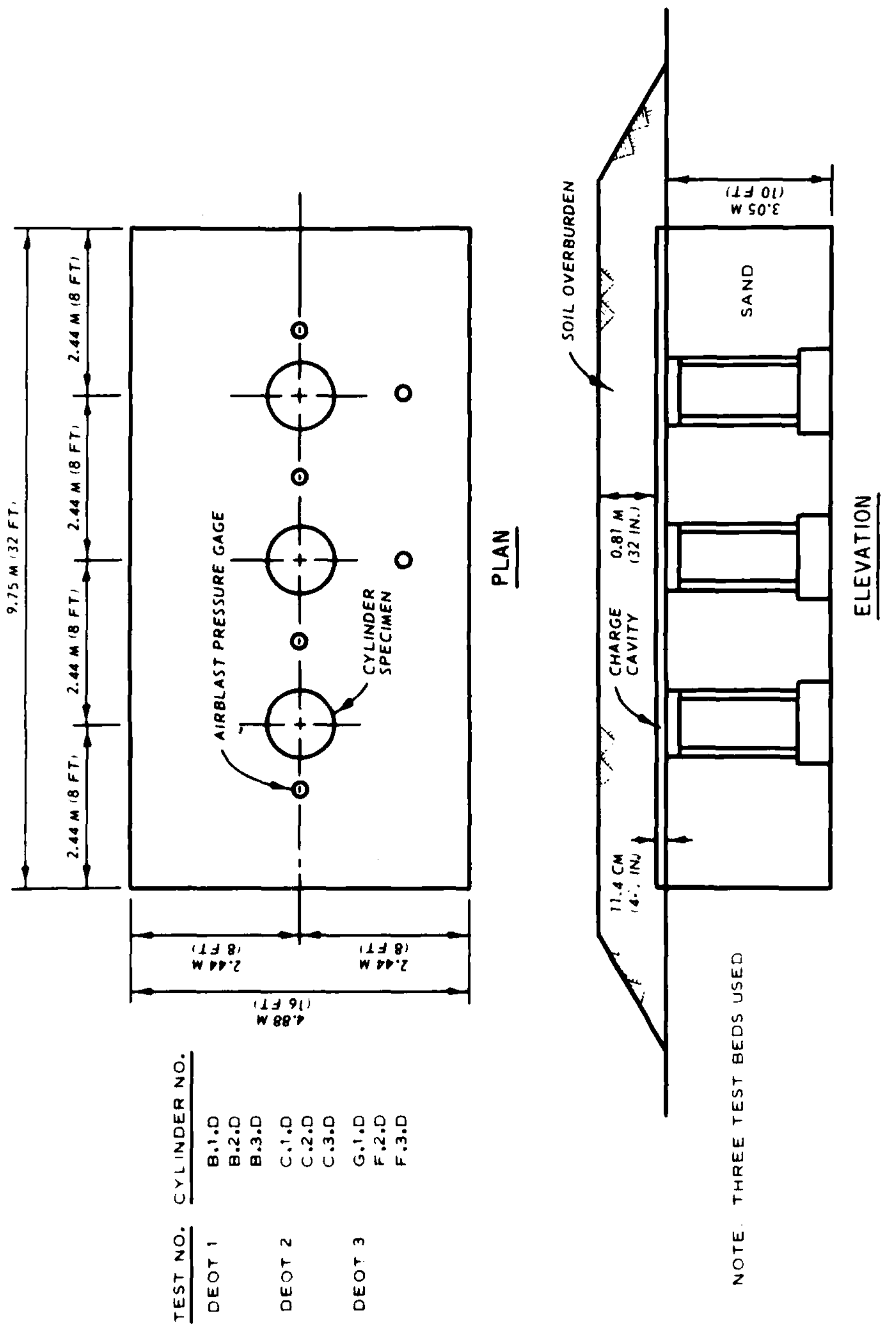

Figure 1. DEOT test bed layout and FOAM HEST configuration

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Figure 2. Cylinders placed on foundations

Figure 3. Backfill around cylinders

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RESULTS AND DISCUSSION

The primary results obtained during this test series include the measured airblast pressure, strain in the cylinder walls, and posttest structural damage. Discussion herein will consider these parameters in an attempt to rank the construction designs as to their survivability/vulnerability.

Test Environment

The planned pressure levels for the tests were 17.2 MPa (2500 psi) for DEOT 1 and 27.6 MPa (4000 psi) for DEOT 2 and 3. It was determined that the average peak pressure for the DEOT 1 test was close to the planned pressure and was 16.1 MPa (2339 psi); the weapon simulation was for an average yield of 13.24 TJ (5.52 kt). For DEOT 2, the average peak pressure was 34.1 MPa (4942 psi) and with a nuclear weapon simulation yield of 56.16 TJ (13.37 kt). The DEOT 3 average peak pressure was somewhat greater than DEOT 2 and was 42.5 MPA (6209 psi); the average weapon simulation yield was 23.66 TJ (3.02 kt). Typical blast pressure curves for the three tests are shown in Figure 4. Although the average peak pressure for DEOT 3 was approximately 26 percent greater than the average for DEOT 2, the average impulse at 10 msec for DEOT 3 indicated an increase of only 12 percent greater than the DEOT 2 average impulse at this same time.

Structural Response

Vertical strain plots from each of the nine cylinders in the three DEOT tests are shown in Figure 5. These strains are for the vertical gage located in the upper portion of the cylinders and oriented toward the detonation side of the test beds. As shown in Figure 5 for the DEOT 1 test (plain concrete with liner) the thinnest wall cylinder B.1.D had appreciably more compressive strain (2000 μin/in) than the other two thicker wall cylinders (1000 μin/in). The two cylinders with wall thicknesses of 7.11 and 10.16 cm (2.8 and 4.0 inches) had approximately the same magnitude of compressive strain. For the pressure obtained, this response infers that there was increased resistance by increasing the wall thickness from 4.32 cm (1.7 inches) to 7.11 cm (2.8 inches) but there appeared to be little additional resistance obtained by increasing the wall thickness to 10.16 cm (4.0 inches).

During the DEOT 2 test on similar constructed cylinders as DEOT 1, but with shear studs, the compressive strains for all three cylinders were approximately 1600 μin/in. The peak pressure for this

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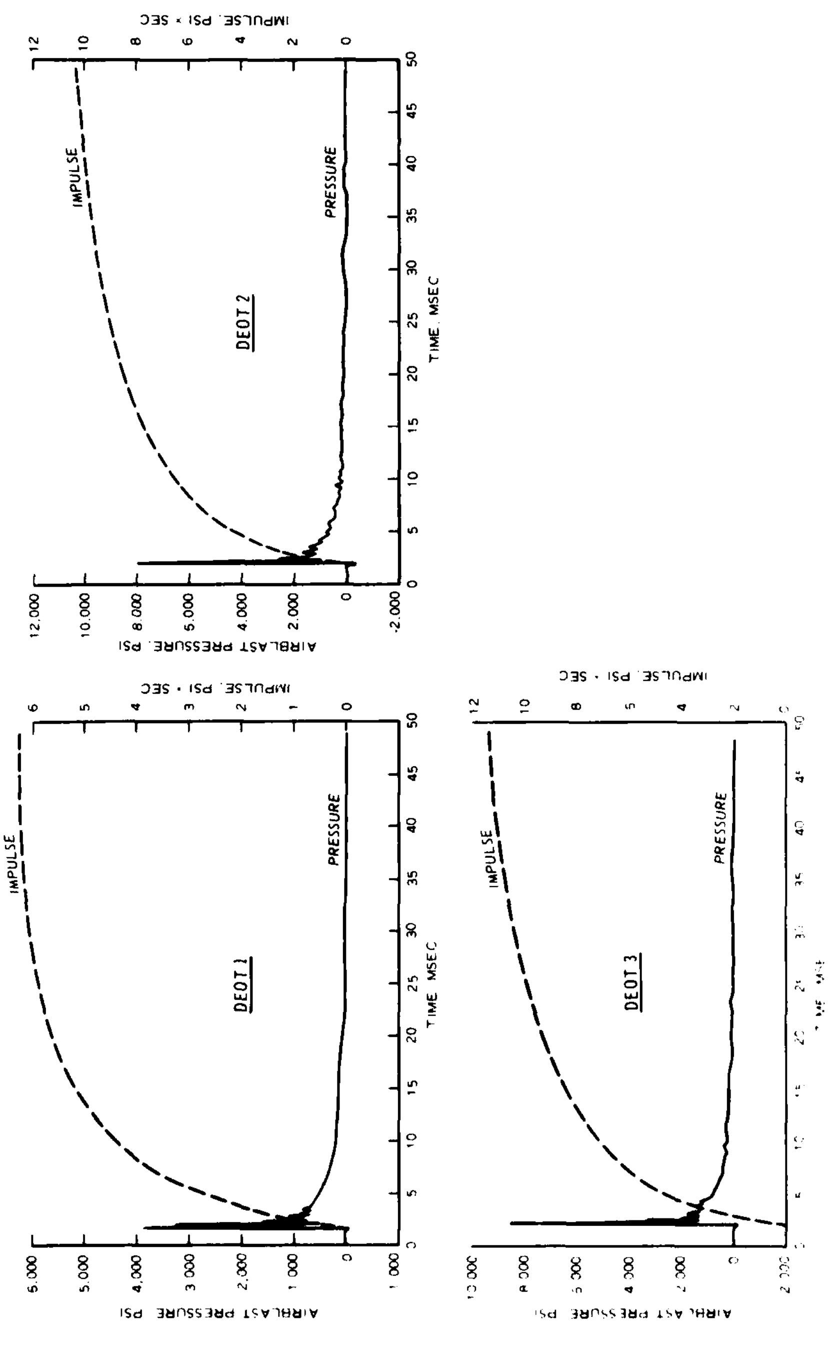

Figure 4. Typical airblast pressure and impulse curves for DEOT tests

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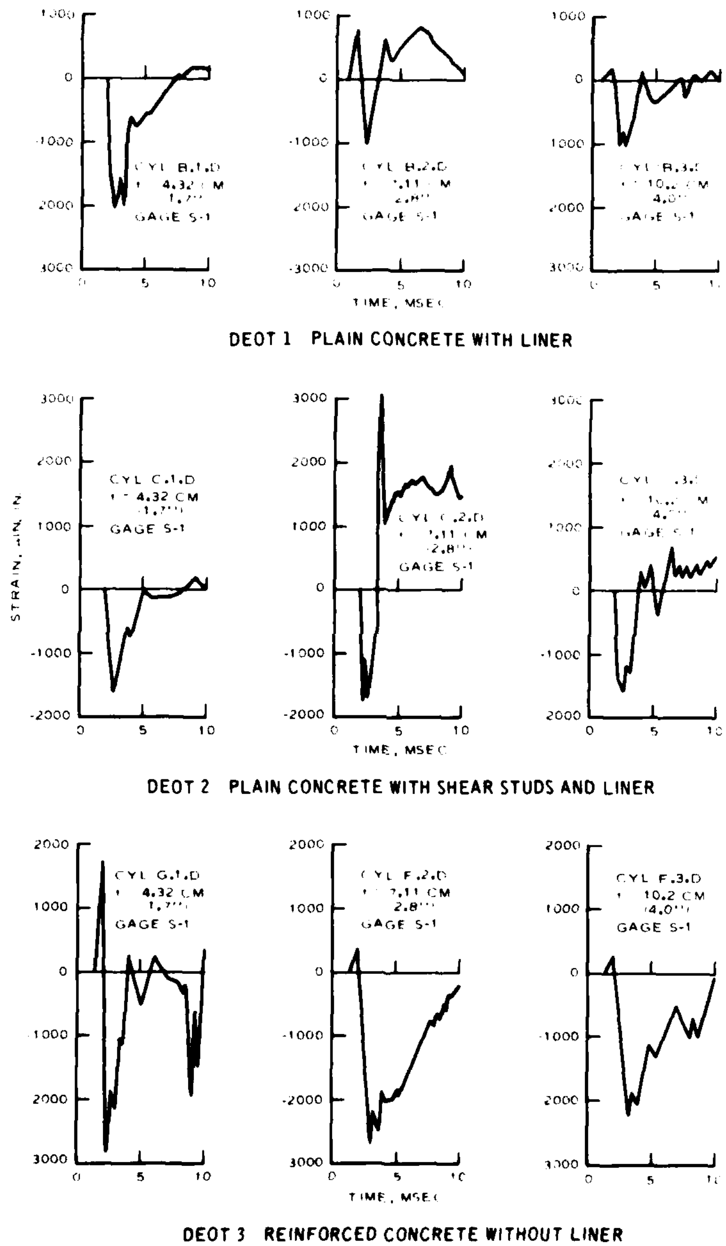

Figure 5. Vertical strain comparison for DEOT cylinders

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test was approximately 2.1 times as great as that for DEOT 1. The fact that all three cylinders of DEOT 2 registered approximately the same strain is believed to be due to the liner, acting along with the shear studs, carrying most of the load. Cylinder C.2.D (middle cylinder) does register more tensile strain than the other two cylinders in the test and this was due to a buckle in the liner occurring at approximately the same location as the strain gage.

For the reinforced concrete cylinders of DEOT 3, the peak pressure was approximately 2.7 times as great as that for DEOT 1. During this test, the peak strains were approximately 2800 μin/in, 2600 μin/in, and 2200 μin/in, respectively, for the thin, middle, and thick cylinders. Thus, there did not appear to be any substantial decrease in the cylinder wall strain level by increasing the wall thickness by factors of 1.6 and 2.4.

It is interesting to compare cylinders with the same wall thickness for the DEOT tests. The comparison will be for the three thinnest cylinders as they incurred various levels of damage. The peak strain levels for the cylinders are:

Test No.	Cylinder No.	Peak Pressure	Pressure Ratio	Peak Strain
DEOT 1	B.1.D	2339 psi	1.0	2000 μin/in
DEOT 2	C.1.D	4942 psi	2.1	1600 μin/in
DEOT 3	G.1.D	6209 psi	2.7	2800 μin/in

These results show that with an increase in peak pressure by a factor of 2.1 for DEOT 2 with respect to DEOT 1 there was a decrease in peak strain from 2000 μin/in to 1600 μin/in. For DEOT 3, the peak pressure increased by a factor of 2.7 over DEOT 1 and there was an increase in peak strain from 2000 μin/in to 2800 μin/in. Thus, based on the strain behavior of these three cylinders with different wall designs, it appears that the cylinder constructed of plain concrete with shear studs and an inner liner was more resistant to dynamic loading than cylinders with other wall design features.

Structural Damage

After the DEOT 1 test, the sand on top of the cylinders end caps was removed and this permitted measuring the displacement of the cylinders relative to the nuts on the hold down rods. The thinnest cylinder B.1.D appeared to have been displaced downward approximately 1.91 cm (3/4-inch). The other two cylinders did not appear to have

moved relative to the nuts, although the nuts were loose. The sand backfill was excavated from around the cylinders in order to conduct a posttest examination of any damage. Posttest check of the cylinders length indicated only that the thinnest cylinder had shortened 1.91 cm (3/4-inch). Posttest views of damage to cylinder B.1.D are shown in Figure 6 after removing the cylinder from the test bed. Damage had occurred completely around the outside of this cylinder and the liner inside was also damaged and showed ripples at approximately the same location at which the concrete was crushed. Both of the thicker cylinders in the DEOT 1 test incurred negligible damage.

Posttest check of the length change of each cylinder in the DEOT 2 test indicated that the thinnest cylinder had been displaced 5.08 cm (2 inches), the middle cylinder had been displaced 0.32-cm (1/8-inch), and there was no apparent displacement of the thickest cylinder. The thinnest cylinder, C.1.D, was found to have circumferential cracks near the top on the exterior. The other two cylinders had negligible cracks on the exterior. However, the inner liner and concrete of the thinnest cylinder was displaced at the cylinder top (Figure 7). The middle cylinder, C.2.D, appeared to have a slight ripple of the liner at approximately one-fourth of the height from the top on the detonation side. There did not appear to be any damage to the interior of the thickest cylinder, C.3.D.

Posttest check of the DEOT 3 cylinders indicated a length change of 9.53, 2.54, and 0.64 cm (3-3/4, 1, and 1/4 inch), respectively, for the thinnest, middle, and thickest cylinder. The thinnest cylinder, G.1.D, had a vertical crack on the exterior which was wide and open completely through the cylinder. The middle cylinder, F.2.D, showed some exterior crushing below the top and some circumferential spalling at approximately midheight. There was also some cracking below the top exterior for the thickest cylinder, F.3.D. Posttest views of damage to the interior of each cylinder are shown in Figures 8 through 10. Damage to these cylinders was more drastic on the inside with considerable crushing and spalling at the cylinder top portion. The overall damage to the DEOT 3 reinforced concrete cylinders was much greater than that observed for the DEOT 1 and 2 cylinders with inner liners.

Relative Cost Comparison

In addition to structural response and damage, it is interesting to compare the relative material and construction costs of the three different designs for prototype cylinders similar to those tested in this program. Actual dollar amounts for the costs will not

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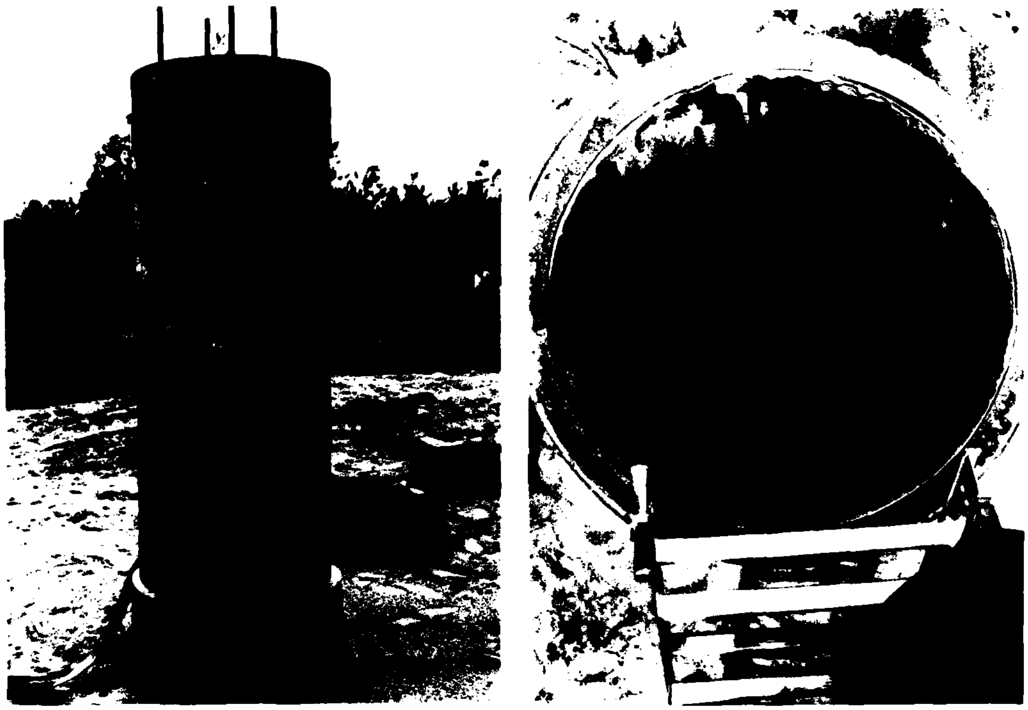

a. Damage to exterior b. Damage to inner liner

Figure 6. Damage to cylinder B.1.D (t = 1.7 in.) during DEOT 1 test

Figure 7. Damage to interior of cylinder C.1.D (t = 1.7 in.) during DEOT 2 test

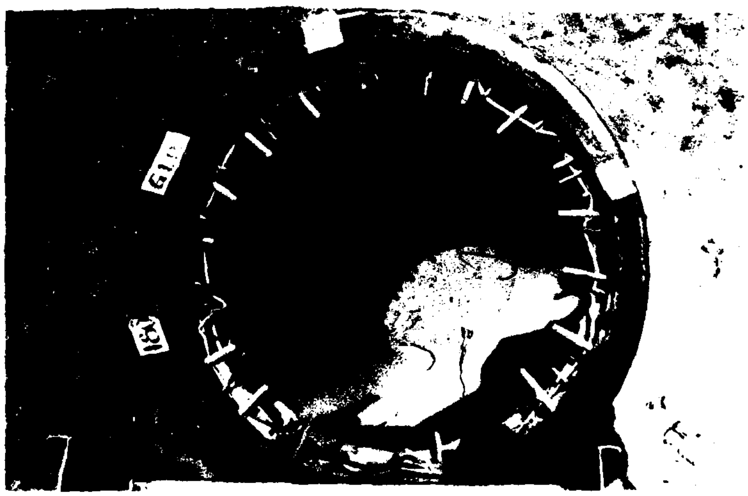

Figure 8. Damage to interior of cylinder G.1.D (t = 1.7 in.) during DEOT 3 test

Figure 9. Damage to interior of cylinder F.2.D (t = 2.8 in.) during DEOT 3 test

Figure 10. Damage to interior of cylinder F.3.D (t = 4.0 in.) during DEOT 3 test

be presented; however, a cost index will be used whereby the cost of each design is normalized by the least cost of the three. The cost index was prepared for the middle cylinder thickness (baseline design). The estimated cost index for prototype cylinder materials and construction including necessary interior and exterior construction forms is given as follows:

Wall Design	Estimated Cost Index
Reinforced concrete without steel liner	1.00
Plain concrete with steel liner	1.37
Plain concrete with steel liner and shear studs	1.42

As shown in the cost index, the reinforced concrete construction without a steel liner is the least cost method. Construction cost with a steel liner is approximately 1/3 more than the reinforced case, and it should be noted that the addition of shear studs does not appreciably change the cost index.

CONCLUSIONS

1. The middle cylinders (baseline design) appeared to have less structural damage than the thinner cylinders and there did not appear to be any significant increase in structural resistance by increasing the wall thickness over the baseline thickness for the overpressure ranges of these tests.

2. Damage to the lined cylinders did not appear to be as severe as the unlined cylinders, i.e. internal spalling of concrete was almost negligible.

3. The results indicate that plain concrete cylinders with inner steel liners and shear studs were more resistant to dynamic loading than reinforced concrete cylinders without internal liners.

4. Although the cost of material and construction for the concrete cylinder with steel liners and studs was approximately 40 percent greater than that for reinforced concrete cylinders, the lined cylinder with studs was proportionately more resistant to dynamic loads.

5. The results of this field test program have shown that the FOAM HEST test environment procedure provides an acceptable simulation technique and was relatively inexpensive to conduct.